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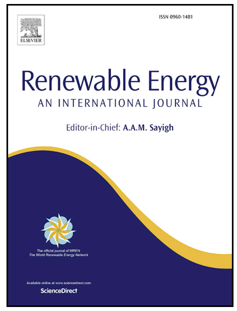

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Abstract

As the marine renewable energy industry evolves, in parallel with an increase in the quantity of available data and improvements in validated numerical simulations, it is occasionally appropriate to re-assess the wave and tidal resource of a region. This is particularly true for Scotland - a leading nation that the international community monitors for developments in the marine renewable energy industry, and which has witnessed much progress in the sector over the last decade. With 7 leased wave and 17 leased tidal sites, Scotland is well poised to generate significant levels of electricity from its abundant natural marine resources. In this state-of-the-art review of Scotland's wave and tidal resource, we examine the theoretical and technical resource, and provide an overview of commercial progress. We also discuss issues that affect future development of the marine energy seascape in Scotland, applicable to other regions of the world, including the potential for developing lower energy sites, and

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grid connectivity.

Keywords: Marine renewable energy, Wave energy, Tidal energy, EMEC, Pentland Firth, Scotland

1. Introduction

If there is one region of the world that is synonymous with marine renewable energy, it is Scotland. With 16,500 km of coastline and a population density of 64/km^2 [1], Scotland is in a strong position to make use of its abundant wave and tidal resources to generate meaningful levels of electricity [2]. Scotland sits on the western fringes of the northwest European continental shelf, exposed to waves propagating from the north Atlantic - the main source of its wave energy resource. In addition, numerous narrow channels, seaways and "firths" interspersed around Scotland lead to the formation of some of the strongest tidal currents in the world, with the Pentland Firth, in particular, often nicknamed the "Saudi Arabia of tidal power" [e.g. 3]. As a consequence of Scotland's abundant natural marine resources, there has been much commercial progress of both wave and tidal energy projects in Scottish waters [e.g. 4], and this progress has been facilitated by the formation, in 2003, of EMEC - the European Marine Energy Centre - in Orkney.

However, the exploitation of Scotland's wave and tidal energy resource from the most energetic sites is hindered by insufficient electrical grid infrastructure. The majority of promising wave power sites are situated around remote island locations, with the greatest tidal energy resource found in channels between islands, or between Scottish islands and the mainland. A strong grid infrastructure between these remote sparsely populated development sites and the main population centres further south is therefore imperative for the further development of projects and marine energy technology in the region.

This article, which reviews the marine energy resource of Scotland, is organised into three main sections - commercial progress (Section 2), tidal resource (Section 3), and wave resource (Section 4). Within each of the resource sections, sites that are currently leased for either tidal or wave energy development are briefly described, followed by a detailed regional assessment of the resource (i.e. encompassing locations that have not necessarily been leased), based on existing studies and new interpretations of numerical models combined with observations. Finally, the article concludes with a discussion of issues affecting future development of marine energy in Scotland, such as exploiting less energetic sites, and grid connectivity (Section 5).

2. Commercial progress

In this section, we explain the role of the European Marine Energy Centre (EMEC) on the development of the marine energy industry in Scotland, and provide an overview of commercial progress of tidal and wave energy.

2.1. European Marine Energy Centre, EMEC

The foundation of EMEC arose from a strong political commitment to foster a wave and tidal energy industry in Scotland. The Atlantic coast of Scotland, including the west coast of Orkney, has a strong wave energy resource. Accessible tidal stream energy sources in both Orkney and

Shetland were identified by early research [5], including a specific site at Fall of Warness, Orkney. A combination of this natural environment and local industrial, academic and governmental support underpinned the selection of Orkney to host test centres. The European Marine Energy Centre (EMEC) was established in 2003, with the wave test centre at Billia Croo on the west coast opening and welcoming the Pelamis 750 device in 2004. The tidal test centre at Fall of Warness opened in 2006, and in 2008 Open Hydro was the first tidal turbine to deliver electricity to the UK grid. New developers continue to deploy at both EMEC sites, as detailed in the following sections. EMEC has expanded to offer a "scale wave site" and a "scale tide site", in addition to the original full-scale, open-sea sites. The template of EMEC has been adopted internationally, but the early establishment of the centre has undoubtedly benefited industrial development in Scotland, including the supply chain.

2.2. Tidal energy developments

At the time of writing, at least six "first generation" seabed-mounted, horizontal axis tidal turbines have completed testing at EMEC, as well as several other devices. MeyGen and Nova Innovation are now installing some of the world's first pre-commercial arrays off Caithness and Shetland, respectively, using machines of this type. MeyGen plan 6 MW of installed capacity in their first phase, using a blend of 1.5 MW units from Atlantis and Andritz Hydro Hammerfest [6]. Nova Innovation are installing five of their own 100 kW devices, and reported the first power supplied to the Shetland grid in March 2016 [7].

Four device developers have announced plans to test "second generation" tidal energy convertor (TEC) designs at EMEC in either 2016 or 2017: Nautricity with the CoRMaT, Sustainable Marine Energy with the PLAT-O platform (using Schottel turbines), Tocardo with their T2 design, and Scotrenewables with the SR2000. These technologies show two notable areas of evolution. Firstly, all are floating designs (optionally in the case of Tocardo), in contrast to earlier seabed-mounted devices; and secondly the emergence, from Schottel and Tocardo, of "bare" turbines sold as components, which are then integrated by others into full TEC systems. It is also interesting to observe a greater diversity of scale. Whereas most first generation machines were rated at 1 MW, new designs range from 100 kW (intended for arrays of many small devices, but also for small-scale off-grid applications) to 2 MW.

2.3. Wave energy developments

An enthusiastic commercial outlook for the wave sector from 2011/12 culminated with the intense full scale testing programmes of then leading developers Aquamarine Power and Pelamis Wave Power at the EMEC test site at Billia Croo, Orkney. This positive outlook was further boosted by the successful delivery of "the world's first commercial wave power station" in Mutriku, Basque Country, by Voith Hydro Wavegen [8]. However, these positive developments suffered severe setbacks with the decision by Voith, in 2013, to withdraw from actively pursuing developments in the wave energy sector, and more recently by the announcement of Pelamis Wave Power and Aquamarine Power calling in administrators and subsequently stopping trading in 2014/15. In effect, that means that the three Scotland based previously globally leading developers in the sector are no longer trading, and it has only been partially possible to capture the wealth of knowledge acquired during intense research, development and field testing programmes during the closures of business of said companies. In response to these developments, the Scottish Government set up Wave Energy Scotland (WES) in 2014 to facilitate a comprehensive R&D programme with a view to bringing wave power technology to commercial market readiness [9]. The initial WES technology development programme supported 16 projects related to power take off technology, and a further 8 projects to develop novel wave energy converter (WEC) technologies. As the programme evolves through the project development stages, the number of participants changes, as only the most promising developments continue to receive support.

Following on from the discontinuation of the previously planned large scale developments, the focus appears to have shifted towards the implementation of smaller projects. A number of novel WEC concepts and subsystem components are currently being developed in a co-ordinated way, funded and overseen by WES, and concepts such as Albaterns WaveNet are already being deployed in conjunction with the aquaculture sector, with a view to small scale power production for local site use. In another active project, the same developer is considering integrated energy solutions at island community scale [10], and given the constraints experienced by a weak electrical grid infrastructure, this appears to be an appropriate interim stage *en route* to up-scaling projects to commercial scale.

The willingness of the private and utility sector to invest in wave power technology and projects is currently at a low level, e.g. due to a high uncertainty on revenue predictions related to electrical infrastructure and transmission costs. Combined with limited confidence in successful project delivery in the near future, programmes that are currently underway by the Scottish Government, through WES, are anticipated to re-create and stimulate conditions that give higher levels of certainty to investors, and are likely to see progression of a new generation of prototypes to commercial stage.

CorPower Ocean, will test a dynamically-tuned point absorber at EMEC in 2016 [11], and Laminaria have announced plans to bring their prototype to Orkney the following year [12].

3. Tidal resource

Scotland is separated from the North Atlantic by relatively narrow (approximately 100 km) shelf seas to the north and west (Fig. 1). The Pentland Firth and the Fair Isle Gap[1], as well as channels through the Orkney & Shetland island groups, connect these shelf sea regions to the North Sea in the east of Scotland, and the North Channel connects the shelf seas to the Irish Sea. Scotland's tides are controlled by the tides in the North Atlantic which, being strongly semi-diurnal, can be described by the principal semi-diurnal lunar (M2) and solar (S2) constituents (Fig. 2). The tidal wave propagates northwards up the western edge of the continental shelf, then turns eastwards across the northern extent of Scotland, before travelling into the North Sea (see the co-phase lines in Fig. 2). Combining

[1] The strait between Orkney and Shetland.

the M2 and S2 constituents, the mean spring tidal range in Scotland is typically 3-4 m, but exceeds 7 m in the Solway Firth (northern Irish Sea) (Table 1), since the Irish Sea is close to resonance for the semi-diurnal frequency [13]. Conversely, there are M2 and S2 amphidromic points[2] in the Malin Sea, between the Mull of Kintyre and Northern Ireland.

3.1. Leased tidal sites

The Crown Estate[3] is responsible for leasing areas of the UK seabed that are suitable for installing wave and tidal arrays, and for managing the associated seabed rights. The Crown Estate have so far granted leases for 30 UK tidal stream sites, 17 of which are in Scotland, and 9 of these are in the waters of the Pentland Firth and Orkney alone (Table 2, Fig. 3). These leased sites range in scale from test sites (namely the 4 EMEC sites), small arrays such as the 30 MW projects in Lashy Sound and the Mull of Galloway, and larger arrays within the Pentland Firth region, such as Brims Tidal array (200 MW) and the MeyGen project in the Inner Sound (400 MW). Reflecting the nature of the resource, the leased tidal stream sites are all located within channels (10 sites) or off headlands (7 sites). The headland sites are in the Pentland Firth (3) and Malin Sea / Irish Sea (4), whereas the channel sites are mainly within the Orkney archipelago (5), one is in the Pentland Firth (the Inner Sound), three are in the west of Scotland, with one further leased site in Shetland (Bluemull Sound).

[2] A point of zero amplitude of the appropriate constituent tide.

[3] The Crown Estate is a statutory corporation that owns virtually all of the UK's seabed from mean low water to the 12 nautical mile (22 km) limit.

3.2. Overview of tidal stream resource

The distribution of the simulated spring tidal current amplitude around Scotland is shown in Fig. 4. Generally, tidal currents are under 1 m/s, but there are many regions, mainly associated with flow around headlands and within channels, where the spring currents exceed 2.5 m/s. Developers value these regions of strong tidal flow, since the power generated is a function of velocity cubed; therefore there is considerably higher energy density in such regions [15]. Associated with these regions of strong tidal flow, the tidal ellipses (also shown on Fig. 4) are generally rectilinear; i.e. the currents are strongly bi-directional. This is in contrast to regions of lower flow, e.g. much of the North Sea, where the tidal currents are more rotary in character. This has important implications on the type of device that is suitable for each of these regions. For instance, a yawing mechanism (or a vertical axis turbine) would be more suited to the lower energy regions around Scotland, whereas a fixed (non-yawing) device would be more suited to the more energetic regions [e.g. 16].

It should be noted, that model simulations at the resolution and spatial extent as those shown in Fig. 4 do not fully resolve the tidal energy resource. For example, at a resolution of around 2 km, many of the channels where much of the resource resides, such as the Inner Sound of Stroma, will not be resolved [e.g. 15]. Detailed site-specific quantification of the resource is reserved for the following sub-sections, where field data is presented in conjunction with higher resolution model simulations.

3.3. Regional tidal resource

3.3.1. Orkney & Shetland

The islands which make up the Orkney and Shetland archipelagos abound with numerous narrow inter-island tidal channels with strong tidal flows that have long been identified with strong potential for tidal energy extraction [5]. In particular, Fall of Warness and Lashy Sound in Orkney, and Bluemull Sound and Yell Sound in Shetland, are recognised as potential tidal energy sites.

Among other data sources, the tidal energy resource discussed in this section (and used to illustrate the Pentland Firth resource in the following section) is based on two validated models of the region. The main features of the two models are provided in Table 3.

Strong tidal flows occur within many of the channels around Orkney (Fig. 5). Currents in excess of 3 m/s are present in Lashy Sound, where peak currents of 3 m/s occur on both the flood and ebb phases of the tidal cycle. In Hoy Sound (at the western approach to the historical Scapa Flow [19]) peak spring currents exceed 4 m/s in the most constricted part of the channel between Graemsay and Stromness (Mainland), and in Burra Sound (between Graemsay and Hoy) peak spring velocities of 3 m/s are typical. Whilst not being as energetic as their neighbouring tidal straits, the tidal currents in The String (a channel between Shapinsay and Mainland Orkney) and Stronsay Firth (between Shapinsay and Stronsay) are also of note, as peak spring tidal flows of 2 m/s can occur. Westray Firth and Stronsay Firth together form the main channel through Orkney, where a large phase difference in tidal elevations at either end of the channel (> 2 h) leads to the generation of strong tidal currents [20]. A large range in asymmetry can be observed in the tidal current resource at these sites. In Westray Firth (between Westray and Rousay), peak spring tidal flows can exceed 3.5 m/s during the southeast-directed flood, but are less energetic on the northwest-directed ebb tide. Stronsay Firth also exhibits flood-dominated asymmetry. However, tides at Fall of Warness, which is located between Westray Firth and Stronsay Firth, display much more symmetrical properties [20]. The EMEC tidal test site at Fall of Warness was chosen for its strong tidal races, which reach almost 4 m/s at spring tides [20].

Power density (Fig. 5) was calculated using the outputs of a 3D numerical model of the region, averaged over a spring tide. The Pentland Firth is the region with the highest power density, followed by Westray Firth, and Lashy Sound.

Shetland has been identified as having potential for both tidal and wave energy developments [21]. Power density maps from the ABPmer Atlas [22] show maximum values of 0.5 kW/m^2 during neap tides, which increases to 2 kW/m^2 during spring tides. Three main areas have been identified as candidate sites for tidal energy development in Shetland: Bluemull Sound (between Unst and Yell islands), which is not fully resolved by the ABPmer Atlas, Yell Sound (the channel between Mainland and Yell), and Sumburgh, the southermost location. The development of a large-scale renewable industry in Shetland is hampered by the absence of an interconnector to the UK National Grid. It was initially anticipated that an interconnector would be in place by 2018, and so there was growing interest in the development of the renewables industry in Shetland [23].

However, more recently, the UK Government withdrew its support for onshore wind, the so called CfD (contract for difference) subsidy, and this casts doubt on the future of this interconnector.

3.3.2. Pentland Firth

The Pentland Firth, which divides Orkney from mainland Scotland and links the northeast Atlantic to the North Sea, is arguably the most concentrated tidal energy resource in the world. The energetic tides in this channel are driven by a combination of physical parameters. Although the tidal range is relatively modest to the north of Scotland (Fig. 2), the large difference in elevation phase between the western and eastern approaches to the Pentland Firth (Fig. 2) generates very strong currents in the channel. Currents are further enhanced by tidal streaming, created by topographic constrictions. The addition of a number of islands within the channel further accelerates local tidal velocities [24]. With its worldwide reputation, the Pentland Firth has had a prominent role in marine renewable energy development, and so several attempts have been made to characterise and quantify the available tidal energy resource [24, 25, 26, 27].

Estimates of the tidal energy potential in these few square kilometres range from 2 GW to 8 GW. It is still unclear how much power might be generated, and estimates in the literature vary considerably from 1 GW averaged over a tidal cycle [28], to around 18 GW at peak flow [29]. Adcock et al. [25] estimated that the maximum available power is about 1.9 GW. This is already less than half of the maximum extractable power calculated by Draper et al. [26], who estimated that approximately 4.2 GW could theoretically be extracted from the Pentland Firth. To put these figures into context, peak electricity demand in the UK is around 50 – 60 GW; hence the tidal currents in the Pentland Firth could contribute significantly to the UK energy mix, and it is important that such resource estimates be accurately constrained.

The significantly different estimates of the Pentland Firth resource are due to different methodologies used to address different research questions. The 4.2 GW estimate of Draper et al. [26] is an upper estimate of the maximum available power; following the method of Garrett and Cummins [30], Draper et al. [26] investigated the optimum thrust to extract the maximum power from the flow, including investigation of the hypothesised flow diversion around Orkney (which they did not find). In Adcock et al. [25], the 1.9 GW figure is based on a more meaningful method of resource assessment. In a resource assessment, the loss of kinetic energy in the flow (i.e. power extracted minus energy lost in mixing behind the turbine) needs to be simulated, but if rows of turbines (i.e. within an array) are to be deployed, then the power at each subsequent row will reduce, becoming uneconomical. To address this, Adcock et al. [25] assumed a blockage ratio of 0.4 within their method, giving an estimate of 1.9 GW in the available power for M2 and S2; and the addition of more constituents will increase this value [31]. Nevertheless, both values are upper-theoretical values, which are related more with resource impact and assessment methods rather than a real "practical" resource assessment for the Pentland Firth - which will be much lower [e.g. 32]; for example, these effects are yet to be fully quantified in resource assessments; blade effects, support structure drag, power capping, shear (see Draper et al. [33]), device siting prohibitions (i.e. shipping and sea bed limitations), etc.

There is 800 MW of leased tidal stream capacity under development in the Pentland Firth (Table 2). The Inner Sound (located between the island of Stroma and the mainland) is the most energetic of the leased sites, and much research effort has been invested in characterising the resource at this site (eg. [34]). Fig. 6 shows the power density for the Pentland Firth calculated using a 3-D ROMS model of the region. A peak power density of 16 kW/m^2 is reached between the islands of Swona and Stroma, during both neap and spring tides, but values in the range 6-8 kW/m^2 extend throughout much of the channel.

Recent modelling work has relied on a single study of currents in the central Pentland Firth at three sites [35]; one within the constriction between Stroma and Swona, and two others to the west and east, respectively. Caution is essential in applying this data, especially from the central site, where data substitution was necessary due to technical faults during the strongest flows. One notable and reliable feature of the data is evidence that a jet forms through the constriction between Stroma and Swona, and persists to the measurement site beyond [36]. Thus, the strongest flow at the eastern site is on the flood flow, where that site is within the emerging flood jet, while at the western site the ebb flow is strongest. The integrated transport through Pentland Firth is fairly symmetrical, but there is evidence of strong localised asymmetry. The complex geography of the Pentland Firth leads to strong reversing eddies forming on the flood and ebb tides, and makes resource characterisation challenging. Asymmetry in the Inner Sound is related to flow behaviour through a curved channel, which follows different pathways on the flood and ebb tide, such that different parts of the Inner Sound can be either flood- or ebb-dominant [34].

3.3.3. West Scotland

The west coast of Scotland is internationally renowned for its scenic beauty and pristine coastal waters. The scattered islands of the Inner Hebrides and the archipelago of the Outer Hebrides create a network of channels, sounds and headlands, leading to enhanced currents and turbulence, eddy generation, and flow separation in the region [37]. Previous studies on the waters to the west of Scotland have largely focused on the non-tidal circulation [38], particularly on the Scottish coastal current [39, 40, 41, 42], tidal mixing fronts [43], and processes in the fjordic sea lochs [e.g. 44]. The dominant semi-diurnal tide in the region is the result of a Kelvin wave[4] propagating northward along the shelf [45]. The tidal range along the western seaboard varies from near-zero close to the island of Islay, where the amphidrome is located (Fig. 2), to around 5 m at spring tides just to the north of Skye [46]. Northward of Skye, the tidal range diminishes slightly. Despite the larger tidal ranges lying to the north, the areas of strongest tidal current are found predominantly in the south, particularly in and around the North Channel (Fig. 4).

From the amphidromic point near Islay, the tide propagates northwards, but tidal currents are diverted through the multiple channels

[4] A Kelvin wave in the ocean balances the Earth's Coriolis force against a topographic boundary such as a coastline.

and straits between islands. The tide therefore tends to propagate into the ends of individual straits by different routes, leading to differences in tidal phase and sea surface height at either end, in turn causing the strong tidal currents observed in, for example, the Sound of Islay [47] and the Gulf of Corryvreckan [48]. The former, with current speeds exceeding 2.5 m/s, is already under consideration as a tidal energy site, with a lease granted to ScottishPower Renewables UK Ltd (Table 2), recently taken over by Atlantis Resources Ltd. The phase difference in the tides at either end of the Gulf of Corryvreckan generates tidal currents in excess of 4 m/s [37], and its turbulence and whirlpools are famously energetic. Counter-rotating eddies form on each flood tide, and are shed as the flood tide weakens and propagate into the Firth of Lorne [48]. The Gulf has not yet been targeted for development, despite having some of the strongest tidal currents in Scottish waters.

To the west and south of Islay, maximum tidal currents reach 4 m/s, associated with the strong flow through the North Channel. This area has been identified for tidal generation, with the West Islay Tidal Energy Park being developed by DP Energy Ltd, and a planned test site under the auspices of EMEC. Further south still, tidal races around the Mulls of Kintyre and Galloway are particularly evident in high-resolution modelling results [15], and these areas are under consideration for development by tidal energy companies.

To the north, in contrast, tidal currents are generally more quiescient, and the area has been developed over the past five decades for finfish and shellfish aquaculture. Tidal currents in the deep water basins of the many fjordic sea lochs along the coast are typically of the order of only a few centimetres per second, and the areas where the currents are much stronger, over the sills, are not suitable for tidal turbines due to the shallow water depths and limited spatial extent of sill regions. Outwith the fjords, the narrow sound between Skye and the Scottish mainland, Kyle Rhea, with tidal currents of up to 4 m/s, had been identified as a potential site, but the lease has recently been relinquished by Atlantis Resources Ltd. Elsewhere in the north-west, opportunities for tidal energy development are limited. Tidal currents in the Sound of Mull, and those through the Tiree Passage both reach about 1 m/s [42]. These current speeds are not currently considered economically viable for tidal energy conversion.

3.3.4. North Sea

In contrast to the energetic regions discussed in the previous three sections, Scotland's North Sea tidal resource is relatively modest. For example, outside of estuaries, the resource tends to be concentrated to the northeast of Aberdeenshire, with peak spring currents of around $0.5-1.5$ m/s, in comparison to current speeds that exceed 4 m/s in the Pentland Firth (Fig. 4). However, and partly due to the reported decline of the North Sea hydrocarbon industry, the North Sea tidal resource could be strategic. Firstly, slowing of the North Sea oil and gas sector has led to spare infrastructure (e.g. port facilities) and a highly skilled workforce who understand the challenges of working in the marine environment. Further, the tidal wave in the North Sea is considerably out-of-phase with the rest of Scotland (Fig. 2), and so generating electricity during times of peak tidal flows in the North Sea would be complementary to generation times in the rest of Scotland, hence reducing net (aggregated) intermittency [e.g. 49]. Finally, there is much demand for electricity along the central belt of Scotland (Glasgow to Edinburgh), and the North Sea tidal resource, in conjunction with favourable grid connection opportunities in the east of Scotland[5], is geographically advantageous to meet such demand.

Two major estuaries on the east coast of Scotland - the Firth of Forth and the Firth of Tay (Fig. 2) - have potential for tidal stream generation. Both have relatively deep regions, e.g. 70 m and 30 m in the Firth of Forth and Firth of Tay, respectively, and both experience relatively fast tidal flows [e.g. 50, 51]. These estuaries are close to high density populations (Edinburgh and Dundee), and are sheltered from wave activity. However, constraints on possible marine renewable energy developments in such regions include extensive inter-tidal areas, and navigation, particularly the Firth of Forth which hosts a major oil refinery, Grangemouth, around 30 km from the mouth of the estuary.

3.3.5. Irish Sea

The Irish Sea has been extensively studied and modelled for decades [e.g. 52, 53, 54]. Tidal conditions in the Irish Sea are the result of two Kelvin waves: one propagating up the Irish Sea from St. George's Channel, and another propagating southwards through the North Channel [55]. The tidal energy resource in the northern Irish Sea is relatively modest in comparison to the Bristol Channel in the southern Irish Sea, which has the second

[5]The 275 kV East Coast transmission line runs the full length of the North Sea seaboard of Scotland

largest tidal range in the world due to near tidal resonance [e.g. 56]; however, the near-resonance of the Solway Firth and complex tidal dynamics of the North Channel, gives the Scottish coastline of this region (the northern Irish Sea) both a tidal range and tidal-stream energy potential [e.g. 57].

Tidal stream areas suitable for development with 1st generation technology have peak spring tidal current speeds above 2.5 m/s [15], shown as yellow colours in Fig. 7a, which was generated using the tidal harmonics of the simulated tide in a ~ 270 m spatial resolution, well validated, 3D ROMS model of the Irish Sea [15]. Suitable tidal range sites require a mean (M2) tidal amplitude greater than 2.5 m [58], and so are shown as the lighter yellow colours in Fig. 7b (namely, the Solway Firth).

The amphidromic point east of Malin Head, near Rathlin Island (see amphidrome shown in Fig. 7) in the North Channel of the Irish Sea, results in a low tidal range north of 55°N and west of 5°W, with the amplitude of the principle semi-diurnal lunar constituent (M2) being less than ~ 1 m (i.e. a mean tidal range of 2 m). The tidal currents associated with this 'Rathlin Island' amphidromic point are further enhanced by hydrodynamic constrictions (i.e. headlands) around the Isle of Islay, Mull of Kintyre and Rhins of Galloway; which is resolved in the ~ 270 m spatial resolution 3D ROMS hydrodynamic model of Lewis et al. [15], shown in Fig. 7.

The two Kelvin waves of the Irish Sea meet in the northern Irish Sea, forming a standing wave system with little variability in high water times around the Isle of Man, with slack water occurring close to high and low water [59]. In contrast, peak current speeds tend to occur at high or low water in the North Channel due to the progressive nature of the tidal wave [59]. The complex tidal system of the northern Irish Sea results in a large tidal range (M2 amplitude > 2.5 m) for the Solway Firth and strong tidal currents around the Isle of Islay, Mull of Kintyre and Rhins of Galloway (see yellow area of Fig. 7).

No tidal range energy schemes are publicly planned for Scottish waters; however the Solway Firth tidal range is large enough to be considered for a tidal energy scheme [e.g. 58]. Indeed, Yates et al. [57] estimated a maximum of ~ 18 TWh/year could be extracted from a Solway Firth barrage which, along with a maximum of ~ 6 GW of tidal-stream energy potential extracted around the North Channel. However, such a large-scale development would lead to significant impacts both on the resource and the environment [60, 61].

The standing wave system around the Isle of Man results in little phase diversity of tidal range and tidal-stream energy schemes [49], particularly as the time of high water is close (within 1.5 hours) for potential tidal range energy schemes in North Wales, Liverpool, Morecombe Bay, and the Solway Firth.

A number of smaller tidal-stream projects are being considered in the Scottish waters of the Irish Sea, at almost every region where the resource is suitable (see Fig. 7), where peak spring tidal currents above 2.5 m/s coincide with water depths in the range of 25 to 50 m [15]. At the time of writing, five tidal stream projects are at the planning stage in the Scottish waters of the northern Irish Sea: a 30 MW lease for the Mull of Galloway, a small prototype planned for Sanda Sound, The Crown Estate's Islay tidal stream demonstration zone, 30 MW West Islay lease, and a 10 MW Sound of Islay development (Table 2).

4. Wave resource

The wave climate of Scotland is generally influenced by conditions in the North Atlantic, since the fetch for the predominantly southwesterly winds is sufficient to generate swell waves [62, 63]. The west of Scotland (Outer Hebrides) and Northern Isles (Orkney and Shetland) are most exposed to the Atlantic, and it is here that the wave resource is at its most energetic [64]. On the east coast of Scotland, conditions in autumn and winter are often energetic in the North Sea when the wind direction corresponds with a large fetch [63]. It has been demonstrated [62], that the winter wave power resource in Scotland correlates well with the North Atlantic Oscillation (NAO) - a climatic index that describes fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high, and which exhibits inter-annual and multidecadal trends [65]. Therefore, although the west of Scotland generally experiences an energetic wave climate, it also exhibits considerable inter-annual variability (in addition to very strong seasonal variability). For example, Mackay et al. [66] found that there was a factor of 2 difference between the lowest and highest monthly mean power levels during winter for a 750 kW (Pelamis) wave energy convertor virtually located to the north of Scotland during the time period 1954-2005, and Neill et al. [64] found that the theoretical mean winter wave power resource varied between 10-40 kW/m over the extended winter (DJFM[6]) period to the west of Orkney over the decade 2003-2012.

4.1. Leased wave sites

The Crown Estate have granted leases for 11 UK wave sites, 7 of which are in Scotland (Table 4, Fig. 3). These sites range in scale from the three EMEC test and demonstration sites, to small (10 MW) arrays (Bernera and Galson, Outer Hebrides), to medium (30 MW) and a large (200 MW) lease off Orkney (Brough Head). With the exception of the EMEC scaled test site in Scapa Flow (Orkney), all of the leased wave sites in Scotland are in waters that are directly exposed to the North Atlantic.

4.2. Overview of wave resource

An overview of the 2006 annual mean wave power and the December 2006 mean wave power around Scotland is presented in Fig. 8. Although there is considerable temporal variability in the wave resource around Scotland [e.g. 62, 64], the spatial trend generally follows the 2006 distribution, since waves tend to emanate from the Atlantic Ocean due to the predominantly southwesterly winds [63]. Based on the validated SWAN wave model of Neill et al. [62], the most energetic area for waves around Scotland, particularly for regions which are relatively close to shore, is to the west of the Outer Hebrides where, in 2006, the annual mean was around 50 kW/m, and the December mean around 130 kW/m. To the west of the Northern Isles, the 2006 mean reduced to around 30 kW/m and 40 kW/m in Orkney and Shetland, respectively, and in comparison to the Outer Hebrides, the

[6] December-January-February-March

December 2006 mean was reduced to 70 kW/m and 100 kW/m to the west of Orkney and Shetland, respectively. Generally, the waters of the Minch (the strait that separates the Outer Hebrides from mainland Scotland), and the North Sea, are both relatively sheltered regions, with a 2006 annual mean wave power of under 10 kW/m (and a December mean of under 20 kW/m). In general, the leased tidal stream sites (Section 3.1) tend to be relatively sheltered from waves; for example, the annual mean wave power at the western approach to the Pentland Firth was around 20 kW/m in 2006; but Islay was slightly more energetic, with an annual mean of around 30 kW/m.

4.3. Regional wave resource

4.3.1. Outer Hebrides

With an unhindered ocean fetch of more than 6000 km in a southwesterly direction towards South America, 3000 km towards Newfoundland and Labrador in the west, and 2000 km and 800 km to Greenland and Iceland, respectively, in the northwest, the Outer Hebrides have one of the most energetic wave resources in the world. The water deepens from the coastline at a shallow gradient of $1-2°$ for approximately 75 km up to a depth of 200m, before the depth rapidly increases to more than 1000 m over the next 20 km. Into the predominant west-southwesterly wave direction, the distance to the continental shelf is around 150 km, and Rockall Bank, with a depth of between 100 to 200 m, is situated some 370 km in the same direction.

Atmospheric low pressure systems originating near the Great Lakes in Canada and following the jet stream into a north-easterly direction are often encountered in the Outer Hebrides, either by direct exposure to these systems and associated strong winds, or by being subjected to swell waves progressing from east Canada or South Greenland towards northwest Scotland [67]. Phenomenal sea states are occasionally observed when low pressure systems progress across the Atlantic at the same speed as the associated waves, a situation described as resonance [68, 69].

Due to the remote nature and very energetic wave climate of the Outer Hebrides, only very limited wave data was available for the area prior to the recently developed interest in wave power exploitation. Early wave measurement campaigns in the area include operation of a wave buoy by the UK Offshore Operators Association (UKOOA) around 60 km northwest of the Outer Hebrides, to establish the 50 year design wave height [70, 71], and a wave buoy array perpendicular westwards to the shore at South Uist, set up and maintained by the Institute of Oceanographic Sciences in 1976 [72, 73, 74, 75]. Following a severe storm event in the area in 2005 with enormous coastal damage, including loss of life, a wavebuoy was also deployed and is still operational at 100 m depth west of South Uist to inform coastal erosion and protection assessments [76].

These early efforts were supplemented more recently in support of wave power resource assessment, when a sensor network consisting of three wave buoys in intermediate depth was deployed along with two bottom mounted acoustic wave sensors in shallow water in 2011/12 under the Hebridean Marine Energy Futures project to provide calibration and validation data for a high resolution spectral wave model [77, 78]. Additional wave measurements have recently taken place in the more sheltered waters to the east of the Hebrides, and in 2016 an X-band radar station, together with two measurement buoys for wave and current monitoring, was set up at the northern tip of the island chain, known as the Butt of Lewis. The combined measurement and modelling efforts have confirmed the strong seasonal variation, but have also shown a strong weekly variability, e.g. with observed power density values in the period between October to December 2011 ranging from only 3.5 kW/m on a calm day up to > 1 MW/m during storm conditions (significant wave heights and peak periods during these events were 0.85 m, 10.6 s and 11.5 m, 15.8 s respectively) [67]. A strong interannual variation is evidenced by observed power densities of 192 kW/m in December 2011, which reduced to 72 kW/m for the same month in 2012. During the summer, monthly averages of less than 10 kW/m are reported [79]. The recent wave measurement campaign from 2011/12 has established an annual mean wave power density of 75.5 kW/m some 15 km offshore in 60 m water depth for that period [79], and this compares against 42.4 kW/m stated by The Scottish Government [80] as a long term average, or slightly less as $30 - 40$ kW/m as published by ABPmer [22]. The predominant wave direction is from the west-southwest in deeper water, and refracts clockwise towards west-northwest during the shoaling process. Directional variability is much reduced at the nearshore shallow water sites targeted for wave power development, and the combination of sensor deployments and numerical modelling has confirmed the presence of energy hotspots in the shallow water zone, together with a narrower wave height distribution compared against deeper water sites as a result of shoaling and wave breaking processes [68, 68].

The 50 year return wave height for the sea area off the Outer Hebrides is given as 15-16 m [71], and significant wave heights of 13 m were recorded in February 2013 by a measurement buoy in 60 m water depth. During the same storm event, the wave height reduced to 7 m in 13.5 m water depth as a result of energy dissipation. The maximum individual wave height measured at the time was 29.4 m in 60 m, but only 10 m at the shallow water sensor location due to depth-induced wave breaking, and this is an important criterion for site and survivability assessment for WECs and other offshore structures [68].

4.3.2. Orkney

The deep water (water depth > 200 m) annual mean wave power resource to the west of Orkney is around 31 kW/m, reducing to 22 kW/m in the nearshore [81]. It has been demonstrated that the theoretical mean power output over an 8 year period at the EMEC wave test site (to the west of Orkney) for a 750 kW rated Pelamis device is 180 kW, with an uncertainty in measurements of order 10 kW [82]. A limited (34 day) summer wave model simulation of the Pentland Firth and Orkney waters demonstrates the differences between the energetic Atlantic-dominated wave climate to the west of Orkney, in contrast to the relatively sheltered waters to the east [83]. Saruwatari et al. [83] also demonstrated that the peak tidal currents in the Pentland Firth can impact the summer wave resource by up to 60% due to wave-current interaction. However, it should be noted that such impacts are considerably greater for shorter period waves typical of summer months, than would be the case for longer period winter waves [84], and hence wave-current interaction is likely to have a relatively modest contribution to the wave power resource when extended to annual timescales, which are dominated by the more energetic autumn/winter months. Rather, waves around Orkney are expected to influence the tidal resource, rather than *vice versa* [85].

The annual cycle of monthly mean wave power resource averaged over a decade from a recent high resolution model simulation demonstrates clearly the seasonal variability of the resource in Orkney waters (Fig. 9), with a stronger ($\sim 30 - 50$ kW/m) resource to the north and west of Orkney during winter months, reducing to < 10 kW/m during summer months [64]. The largest resource is generally located to the north of Orkney, with a significant resource to the west, and minimal resource (< 15 kW/m throughout the year) to the east of Orkney. In general, there is more uncertainty within the energetic wave resource to the north and west of Orkney, and lower uncertainty to the east of Orkney [64]. However, when expressed as a percentage (i.e. uncertainty in the resource divided by the magnitude of the resource), there is relatively low ($\sim 30\%$) uncertainty to the west of Orkney during winter months, increasing to $\sim 40\%$ during autumn months. In contrast, there is high uncertainty ($\sim 60\%$) in the modest resource to the east of Orkney during winter months, which reduces to $\sim 35\%$ in the autumn. Several studies demonstrate that there is a strong positive correlation between the North Atlantic Oscillation (NAO) (see introduction to Section 4) and the winter wave power resource to the north and west of Orkney [64, 66]. Since the NAO exhibits considerable interannual variability, it is important that this variability is captured by any wave resource assessment of the region, so that the time window used to quantify the wave power resource of Orkney is representative.

5. Discussion

As reflected in the marine renewable energy sites that have been leased in Scotland (Table 2 and Table 4), the industry is primarily focused on developing high energy wave and tidal sites, by installing arrays of large (of order 1 MW) turbines. However, if we consider growth of the wind energy industry over the last 40 years [86], progress from modestly rated (~ 100 kW) to current generation (up to 8 MW) devices was a relatively slow process. Therefore, developing devices that are suitable for exploiting lower energy wave and tidal regions could be strategic for growth in the marine renewable energy industry, prior to facing the challenges associated with developing more energetic sites. In addition, the highly energetic tidal stream sites around Scotland are generally in phase with one-another [e.g. 87], and so the aggregated electricity that would be supplied to the grid would be characterised by strong (semi-diurnal) intermittency, and hence undesirable from a grid integration perspective. The development of lower energy sites would considerably increase this phase diversity [49]. Further, although the wave resource around Scotland exhibits a strong seasonal signal that is advantageous for electricity generation (stronger autumn/winter signal when demand for electricity is higher), it suffers from significant interannual variability [62]. Lower energy sites have considerably less interannual variability [64], and so the development of less energetic wave sites (in parallel with the development of high energy sites) could lead to more consistent (albeit lower magnitude) electricity generation. In addition, the co-location of wave power systems with, for example, aquaculture installations, offers great benefits, as generated electricity can be consumed directly by the fish farms, thus reducing the requirement for expensive on-site diesel generation, and avoiding the need for cable runs to shore. Remote island communities also often depend on local fossil fuel based electricity generation, and even in modest wave climates wave power presents an opportunity for both reduction of generation cost and carbon emissions [10, 88].

One of the reasons for the lack of progress in commercialisation of the wave power sector is linked to the remoteness of the prime wave power sites - for example, an asset map published online by The Crown Estate [89] indicates that at present, all Scottish wave power sites are situated in island locations. This results in increased project costs, e.g. through higher vessel mobilisation charges, but more so through prohibitive costs for electrical grid connection, where such a connection is available. But more often an electrical connection is not available at all, which has been a severe hindrance to attracting private sector investment in the recent past. Due to current uncertainty in the construction of HVDC (high voltage direct current) interconnector cables to provide sufficient capacity to connect large scale wave and tidal power generation sites to the national electrical grid, a number of studies have investigated alternative scenarios to provide grid capacity for marine energy developments in the absence of large scale grid reinforcements. In an assessment of wind and wave resources for the Outer Hebrides, it has been demonstrated that the combination of wind turbines and wave energy converters can maximise grid utilisation where rated generation capacity exceeds the grid connection allowance [90]. Bell [91] used an Orkney case study to demonstrate the benefits of an electrical grid sharing approach between wind, wave and tidal energy generators, considering individual resource intermittencies and its impact on generation patterns. The increased grid utilisation efficiency and ability to meet customer demand by balancing generation capacity across wave and wind power is shown by Samuel [92, 93] as the results of a power flow modelling study on the Outer Hebrides electrical grid, and considering a variety of different generation patterns. Samuel [92, 93] suggests that the currently often used 'connect and manage' grid access system is inadequate to fully exploit wind and wave power generation opportunities in the area, but that the implementation of an actively managed real-time network control offers a partial alternative to radical network reinforcements. However, only an upgrade to the electrical grid infrastructure at local, regional and national scale, including construction of subsea interconnector cables to Outer Hebrides, Orkney and Shetland, can enable full utilisation of the large wave and tidal energy resource available in Scotland.

The theoretical upper limit to power extraction by a wind turbine is constrained by the *Betz limit* ($C_p = 0.59$), where C_p is the rotor power coefficient. In contrast, when tidal turbines are placed in a tidal channel, the turbine blockage ratio increases, resulting in a theoretical C_p of several times the Betz limit for configurations that have high blockage ratios [94]. However, the situation is complicated by the fact that by increasing the blockage ratio of a channel, there will be a corresponding reduction in the free-stream flow due to the increased drag that is a consequence of tidal energy conversion. Although much research on blockage has focussed on theoretical tidal channels [e.g. 95, 96], a special case is the Inner Sound of the Pentland Firth (Fig. 6). At high blockage ratios, a tidal channel that is isolation would theoretically lead to an increase in the power output, despite a reduction in the free-stream flow. However, in the case of the Inner Sound, a high blockage ratio may not have this desired effect, since a portion of the flow would simply by-pass the Inner Sound, in favour of the main channel of the Pentland Firth. Although this issue has not been explicitly addressed by research to date, it has been investigated at a larger scale, and shown that tidal energy extraction from the Pentland Firth does not divert currents around Orkney [26].

It has been noted that the characterisation of nearshore waves in Scottish waters is complicated by strong wave-current interactions in regions such as the Pentland Firth [97]. Indeed, wave-tide interaction is a noted effect near sites of potential wave and tidal energy projects in Orkney waters [83]; hence, dynamically coupled models are necessary for accurate resource assessment in these regions [e.g. 98]. Similar findings have been reported by Guillou et al. [99] when examining the influence of waves on the tidal energy resource of the Fromveur Strait (France), and they concluded that waves affected the tidal resource during extreme conditions by up to 12%, which can have significant implications for cost-benefit analysis of potential tidal projects in such regions. The authors of the present review article recommend that, to reduce uncertainty in wave, and particularly tidal, resource assessments, high resolution validated 3D models should be developed, including 3D tidal energy extraction [e.g. 17], and wave-current interaction when appropriate.

Although it is recognised that turbulence could significantly affect the performance and fatigue of tidal turbines [100], there is currently no standard, universally accepted method of measuring and characterising turbulence at tidal energy sites. Observations from the Fall of Warness (Orkney) have been used to evaluate Reynolds stresses, TKE (turbulent kinetic energy) density, the rates of TKE production and dissipation, and the local eddy viscosity [101]. The TiME project (Turbulence in Marine Environments) funded by the Scottish Government's Marine Renewables Commercialisation Fund (MRCF) is currently attempting to address the issue of turbulence measurements at the Sound of Islay and the Inner Sound of the Pentland Firth using a wide range of instruments, including ADCPs and the *Nemo* turbulence buoy. Accurate *in situ* characterisation of turbulence in regions of strong tidal flow is an important goal for the marine energy industry, and Scotland presently holds the key to unravelling this problem.

Climate change is one of the main driving forces behind the development of renewable energy. However, climate change, particularly sea-level rise, could affect the marine renewable energy resource itself. Global mean sea level is likely to rise by $0.44 - 0.74$ m (above the $1986 - 2005$ average) by 2100 [102]. Given the relatively small tidal range around much of Scotland, particularly in the Pentland Firth and Malin Sea, the Scottish tidal energy resource could therefore be sensitive to such changes, which could alter the tidal dynamics, for example shifting the position of the amphidrome in southwest Scotland (Fig. 2). Studies suggest that storminess will increase over the North Atlantic and northwestern Europe over the next century [103]. However, against a background of an already high interannual variability in the wave power resource, such a future change in storm intensity is not expected to have a significant influence in quantifying Scotland's wave resource over long timescales. Further, when device characteristics are taken into consideration, such as a wave energy convertor entering survival mode during extreme wave conditions, the future technical wave resource is likely to exhibit considerably less variability than the future theoretical wave resource [64].

6. Conclusions

This article has provided insights into the energetic wave and tidal regions of Scotland from both oceanographic and resource perspectives. Useful information has been assembled on commercial progress in marine energy in Scotland, currently leased sites, and locations that could be suitable for future development. Our general perspective is that, in parallel with development of high energy sites, less energetic wave and tidal sites should also be considered, since such environments offer the combined benefits of (a) more tidal energy phase diversity, and hence more potential for firmer power generation when aggregating electricity generated from discrete sites, (b) a more consistent, albeit lower magnitude, wave resource, partly offsetting the significant interannual variability that characterises high energy wave sites, and (c) less challenging environments in which to operate, and hence perfect skills and technologies, before subsequent deployment in higher energy environments.

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1143 **TABLES**

Location	Amplitude (m)		Range (m)	
	M2	S2	Spring	Neap
Leith (Firth of Forth)	1.79	0.61	4.80	2.36
Dundee (Firth of Tay)	1.66	0.53	4.38	2.26
Aberdeen	1.30	0.44	3.48	1.72
Wick	1.02	0.35	2.74	1.34
Kirkwall (Orkney)	0.84	0.29	2.26	1.10
Lerwick (Shetland)	0.58	0.21	1.58	0.74
Stornoway (Lewis)	1.39	0.55	3.88	1.68
Ullapool	1.50	0.58	4.16	1.84
Oban	1.09	0.47	3.12	1.24
Southend (Kintyre)	0.71	0.20	1.82	1.02
Greenock (Firth of Clyde)	1.21	0.32	3.05	1.77
Stranraer (Irish Sea)	1.10	0.29	2.78	1.62
Hestan Islet (Solway Firth)	2.76	0.86	7.24	3.80

Table 1: Amplitude of M2 and S2 tidal constituents, and spring/neap tidal range around Scotland. Locations are shown on Fig. 2a. Data from Admiralty Tide Tables.

Ref	**Site name**	**Tenant name**	**Project status**	**Capacity (MW)**
1	Ness of Duncansby	Atlantis Resources Ltd.	In development	100
2	Westray South	Westray South Tidal Development Ltd.	In development	200
3	Brough Ness	Sea Generation (Brough Ness) Ltd.	In development	100
4	Fall of Warness	EMEC Ltd.	Operational	n/a
5	Sound of Islay	Atlantis Resources Ltd.	Pre-construction	10
6	Inner Sound	MeyGen Ltd.	Under construction	400
7	Bluemull Sound	Nova Innovation Ltd.	Under construction	0.5
8	Shapinsay Sound	EMEC Ltd.	Operational	n/a
9	Lashy Sound	Scotrenewables Tidal Power Ltd.	In development	30
10	Sanda Sound	Oceanflow Development Ltd.	Under construction	0.035
11	Mull of Kintyre	Argyll Tidal Ltd.	In development	3
12	Brims Tidal Array	Brims Tidal Array Ltd.	In development	200
13	Stronsay Firth	EMEC Ltd.	In planning	n/a
14	Islay Demonstration Zone	EMEC Ltd.	In planning	n/a
15	Mull of Galloway	Marine Current Turbines Ltd.	In development	30
16	Kyle Rhea	Atlantis Resources Ltd.	In planning	8
17	Isle of Islay (West Islay)	DP Marine Energy Ltd.	In planning	30

Table 2: Leased tidal sites in Scotland (data from `http://www.thecrownestate.co.uk`).

Model characteristic	Goward-Brown et al. [17]	Waldman et al. [18]
Model	ROMS	Delft3D-FLOW
Horizontal resolution	500 m	200 m
Number of vertical levels	10	10
Source of boundary conditions	GEBCO	TPXO
Tidal constituents	M2, S2	M2, S2, N2, K2, K1, O1, P1, Q1, MF, MM
Turbulence scheme	k-epsilon	k-epsilon
Drag coefficient	$C_D = 0.005$	$C_D = 0.004$

Table 3: Configurations of the two models used to describe the Orkney and Pentland Firth tidal resource. Note that the equivalent drag coefficient is reported for the Delft3D model, since this is imposed in the model using Chezy.

Ref	Site name	Tenant name	Project status	Capacity (MW)
1	Bernera, Isle of Lewis	Pelamis Wave Power Ltd.	Agreement terminating	10
2	Scapa Flow	EMEC Ltd.	Operational	n/a
3	Billia Croo	EMEC Ltd.	Operational	n/a
4	Harris Demonstration Zone	EMEC Ltd.	In development	n/a
5	North West Lewis	Lewis Wave Power Ltd.	Development on hold	30
6	Brough Head	Brough Head Wave Farm Ltd.	Development on hold	200
7	Galson, Isle of Lewis	Lewis Wave Power Ltd.	Development on hold	10

Table 4: Leased wave sites in Scotland (data from `http://www.thecrownestate.co.uk`).

FIGURE CAPTIONS

Figure 1: Bathymetry around Scotland. Contours are depths in metres relative to mean sea level.

Figure 2: (a) M2 and (b) S2 co-tidal charts. Colour scale is amplitude H (m) and contours are phase g in degrees relative to Greenwich. Since the S2 constituent has a period of exactly 12 h, a 30° phase difference in S2 (i.e. the contour interval) represents a time lag of 1 h. Similarly, 30° phase difference in M2 (which has a period of 12 h 25 min) represents a time lag of 1 h 2 min. Amplitude and phase data are from the model described by Hashemi et al. [14].

Figure 3: Leased wave and tidal sites in (a) Scotland, and (b) Pentland Firth and Orkney waters. Tidal sites are coloured green, and wave sites orange. Further details on the sites can be found in Table 2 (tidal sites) and Table 4 (wave sites).

Figure 4: Simulated peak spring tidal current amplitude (colour scale in m/s) around Scotland, and M2 tidal current ellipses (black lines). Data is from the model described by Hashemi et al. [14]

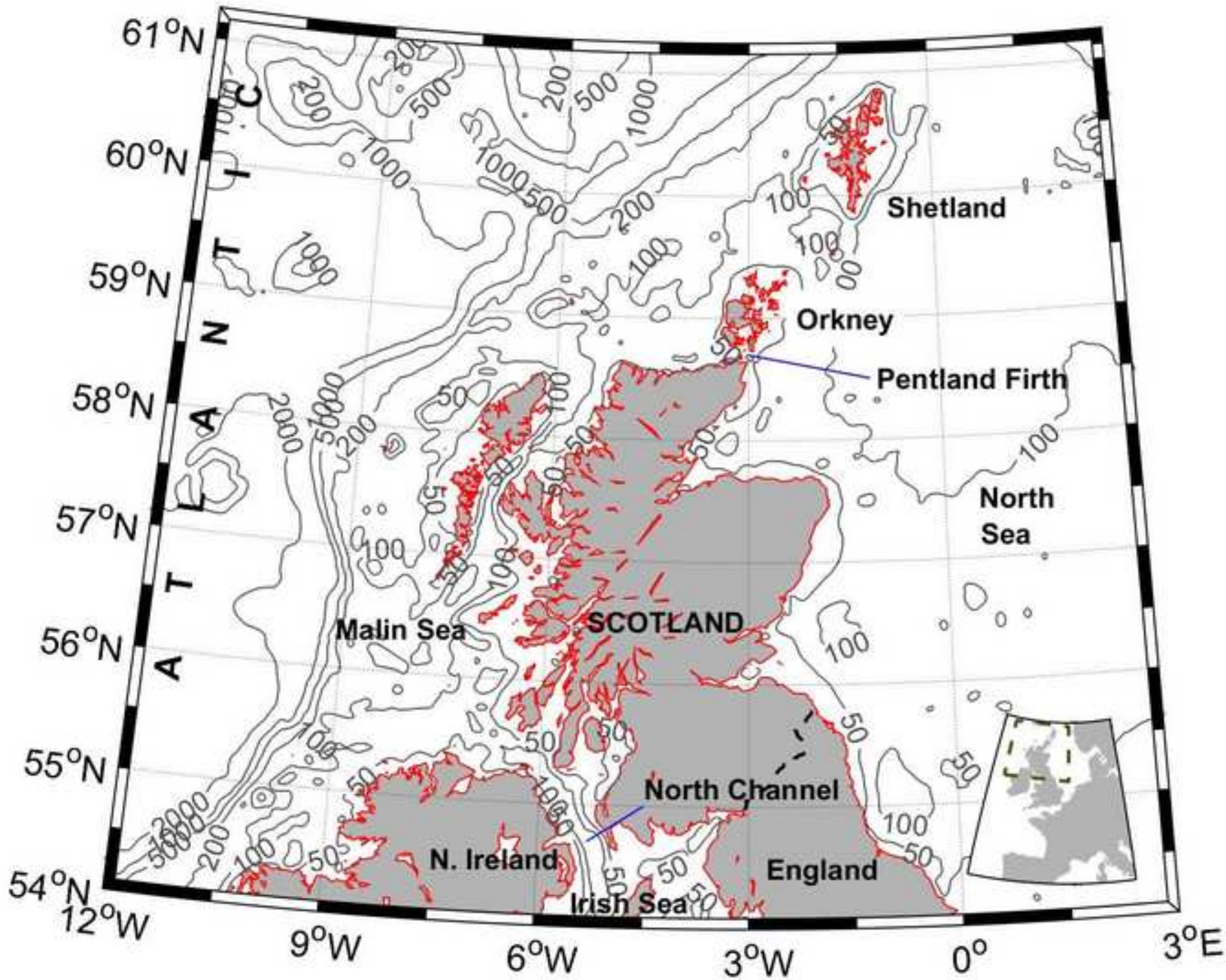
Figure 5: Mean power density (kW/m^2) in Pentland Firth and Orkney waters during spring tides. Contours are only plotted for regions where this value exceeds 1 kW/m^2. Data is from the model described by Goward-Brown et al. [17].

Figure 6: Mean power density (kW/m^2) in the Pentland Firth during spring tides. Contours are only plotted for regions where this value exceeds 1 kW/m^2. Data is from the model described by Goward-Brown et al. [17].

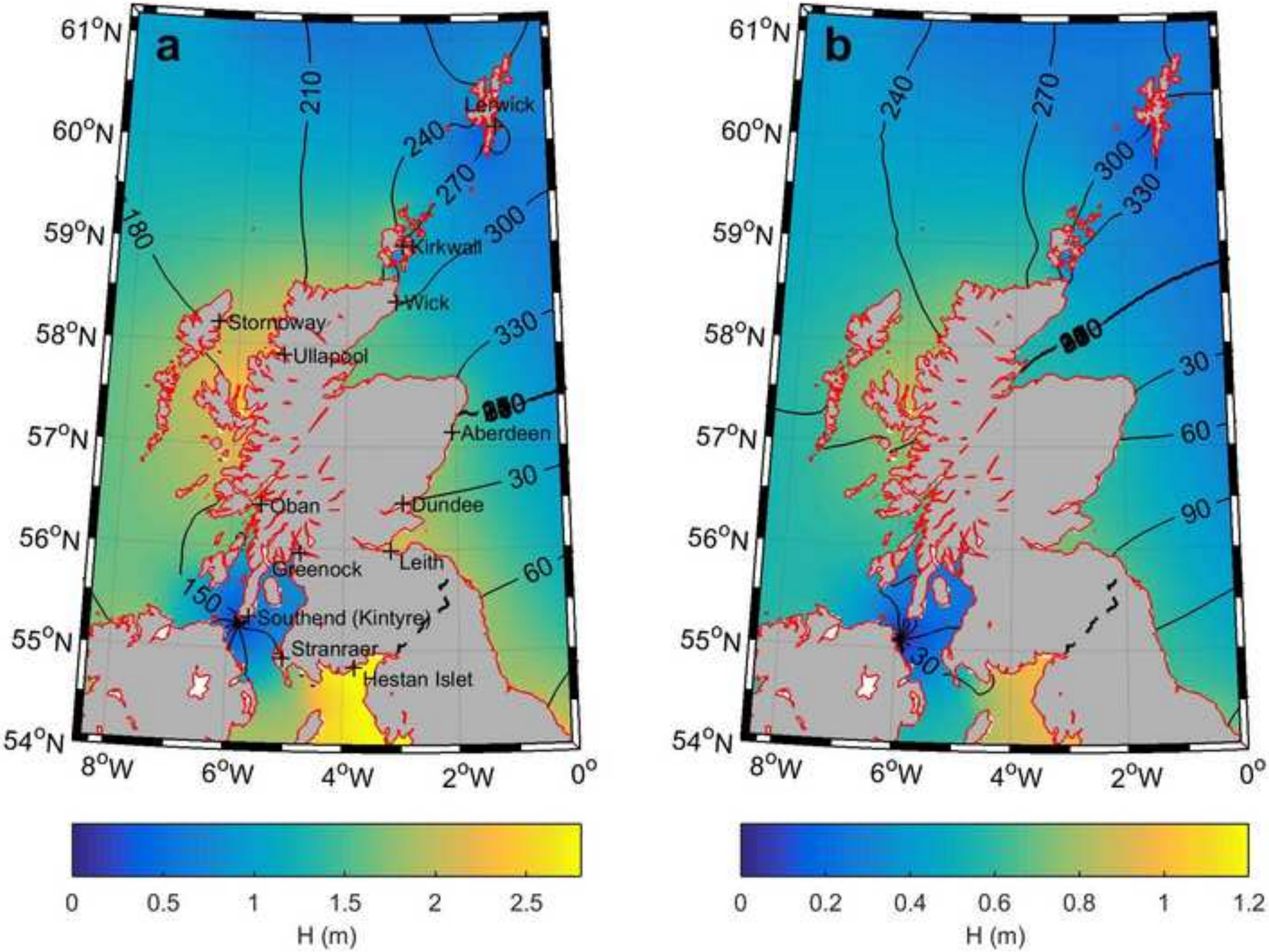
Figure 7: Tidal co-phase charts of the north Irish Sea from the ROMS model of Lewis et al. [15]. (a) peak spring tidal current speeds (m/s) with lines of equal phase (degrees relative to GMT). (b) mean tidal amplitude (M2 amplitude in m) with lines of equal phase. The contour interval is 30° in both (a) and (b).

Figure 8: Mean wave power (kW/m) in Scottish waters during 2006; (a) annual mean, (b) December mean. Data is from the model described by Neill et al. [62].

Figure 9: Annual cycle of monthly mean wave power around Orkney, averaged over 10 years of high resolution model simulation. Reproduced from Neill et al. [64] with permission from Elsevier.



61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
12°W
9°W
6°W
3°W
0°
3°E
ATLANTIC
Shetland
Orkney
Pentland Firth
North Sea
SCOTLAND
Malin Sea
North Channel
N. Ireland
England
Irish Sea


a
b
Lerwick
Kirkwall
Wick
Stornoway
Ullapool
Aberdeen
Oban
Dundee
Greenock
Leith
Southend (Kintyre)
Stranraer
Hestan Islet
61°N
60°N
59°N
58°N
57°N
56°N
55°N
54°N
8°W
6°W
4°W
2°W
0°
210
240
270
300
330
180
150
30
60
90
H (m)
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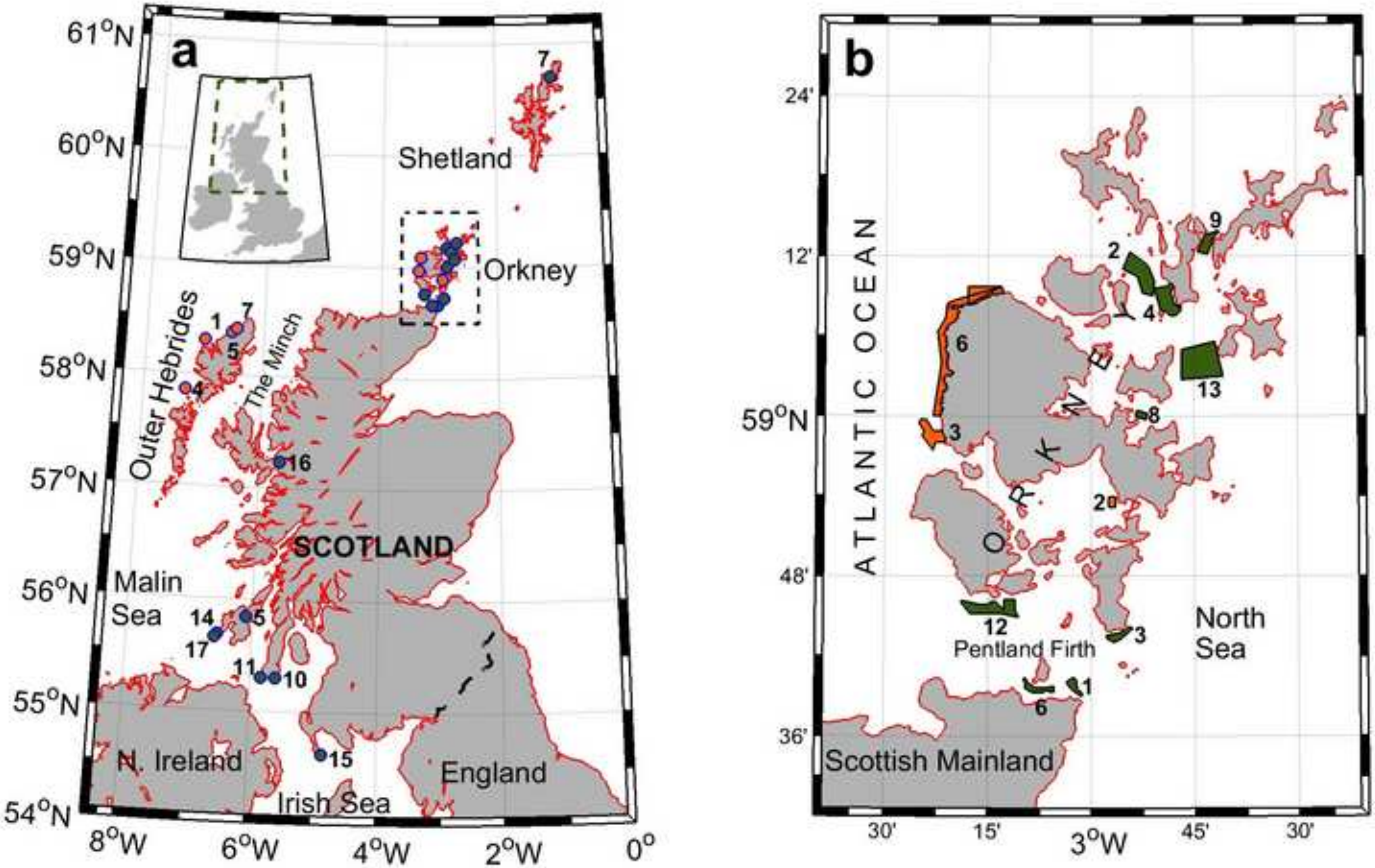
1.2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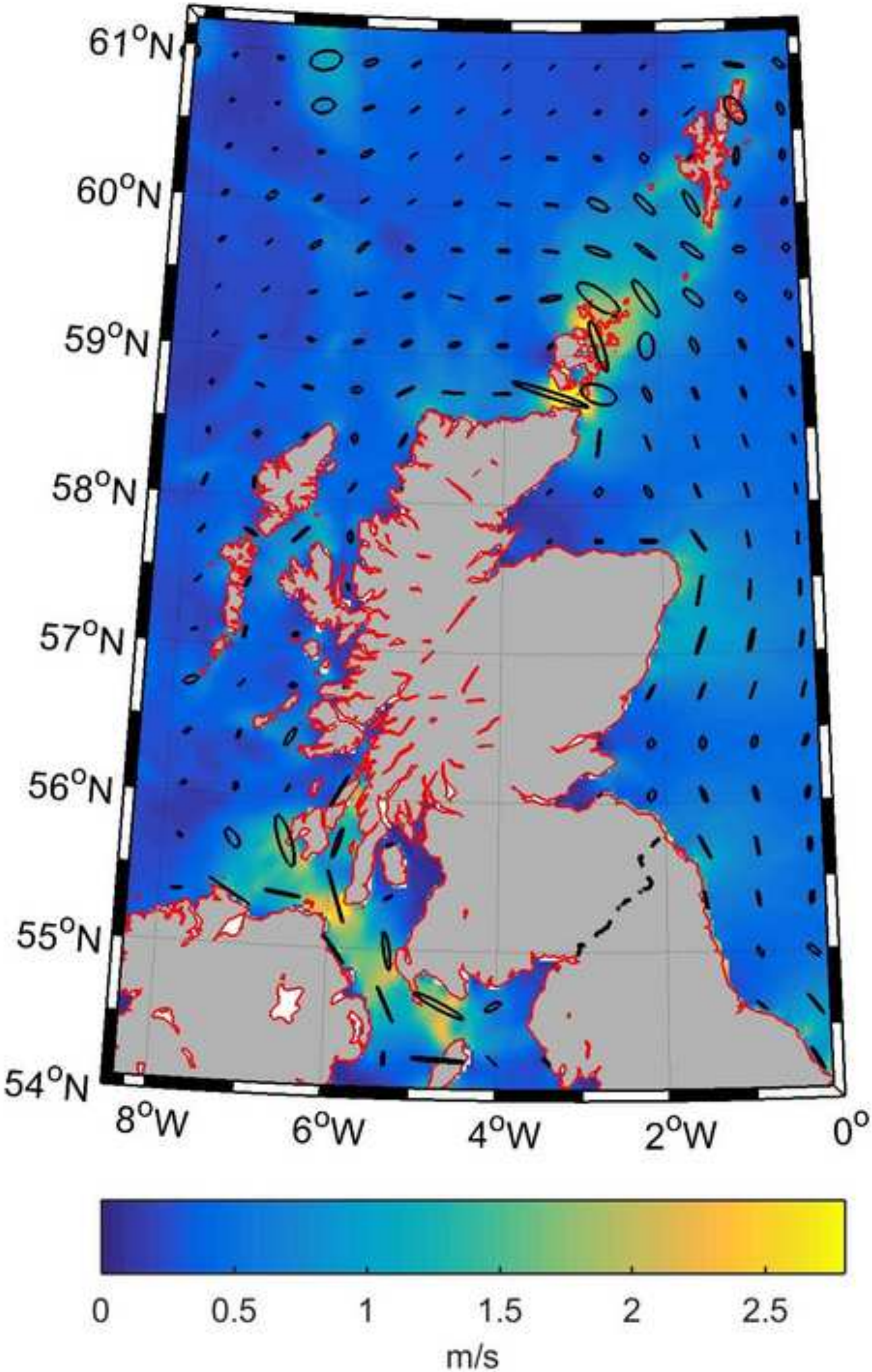
55°N
54°N
8°W
6°W
4°W
2°W
0°
Shetland
Orkney
Outer Hebrides
The Minch
SCOTLAND
Malin Sea
N. Ireland
Irish Sea
England
1
4
5
7
10
11
14
15
16
17
b
24'
12'
59°N
48'
36'
30'
15'
3°W
45'
30'
ATLANTIC OCEAN
ORKNEY
North Sea
Pentland Firth
Scottish Mainland
1
2
3
4
6
8
9
12
13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1
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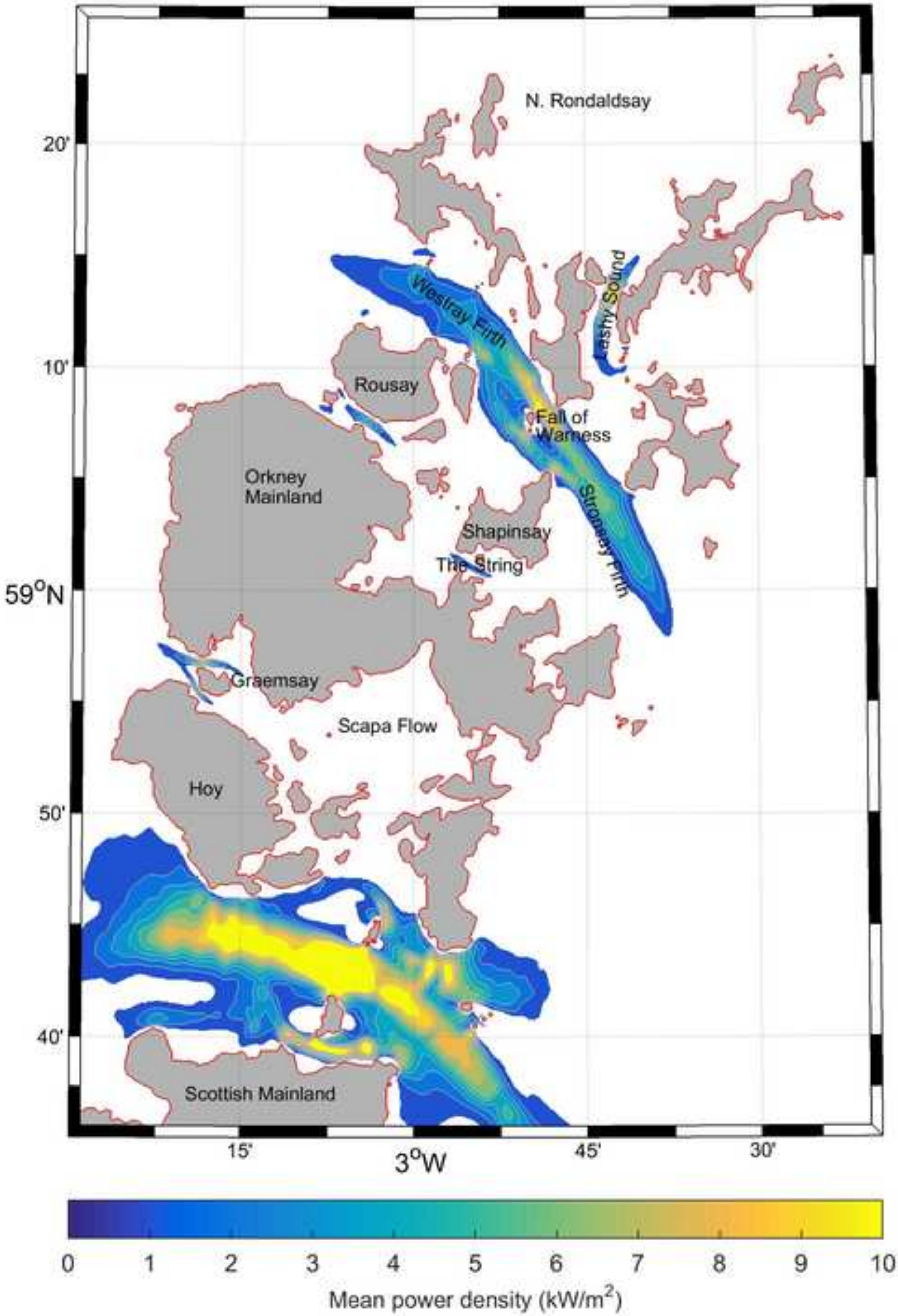
2
2.5
m/s


N. Rondaldsay
20'
Westray Firth
Lashy Sound
10'
Rousay
Fall of
Warness
Orkney
Mainland
Shapinsay
Stronsay Firth
The String
59°N
Graemsay
Scapa Flow
Hoy
50'
40'
Scottish Mainland
15'
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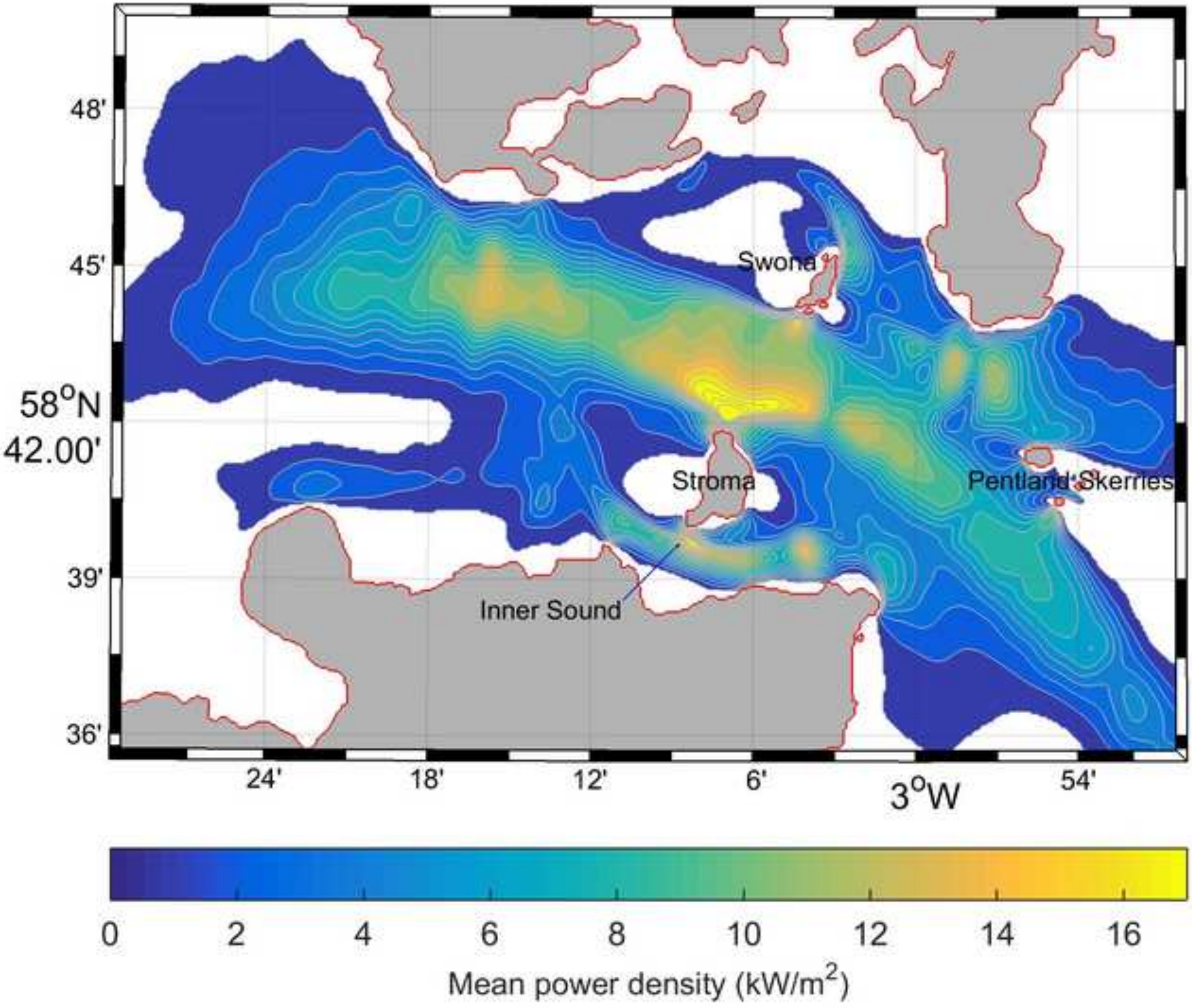
10
Mean power density (kW/m²)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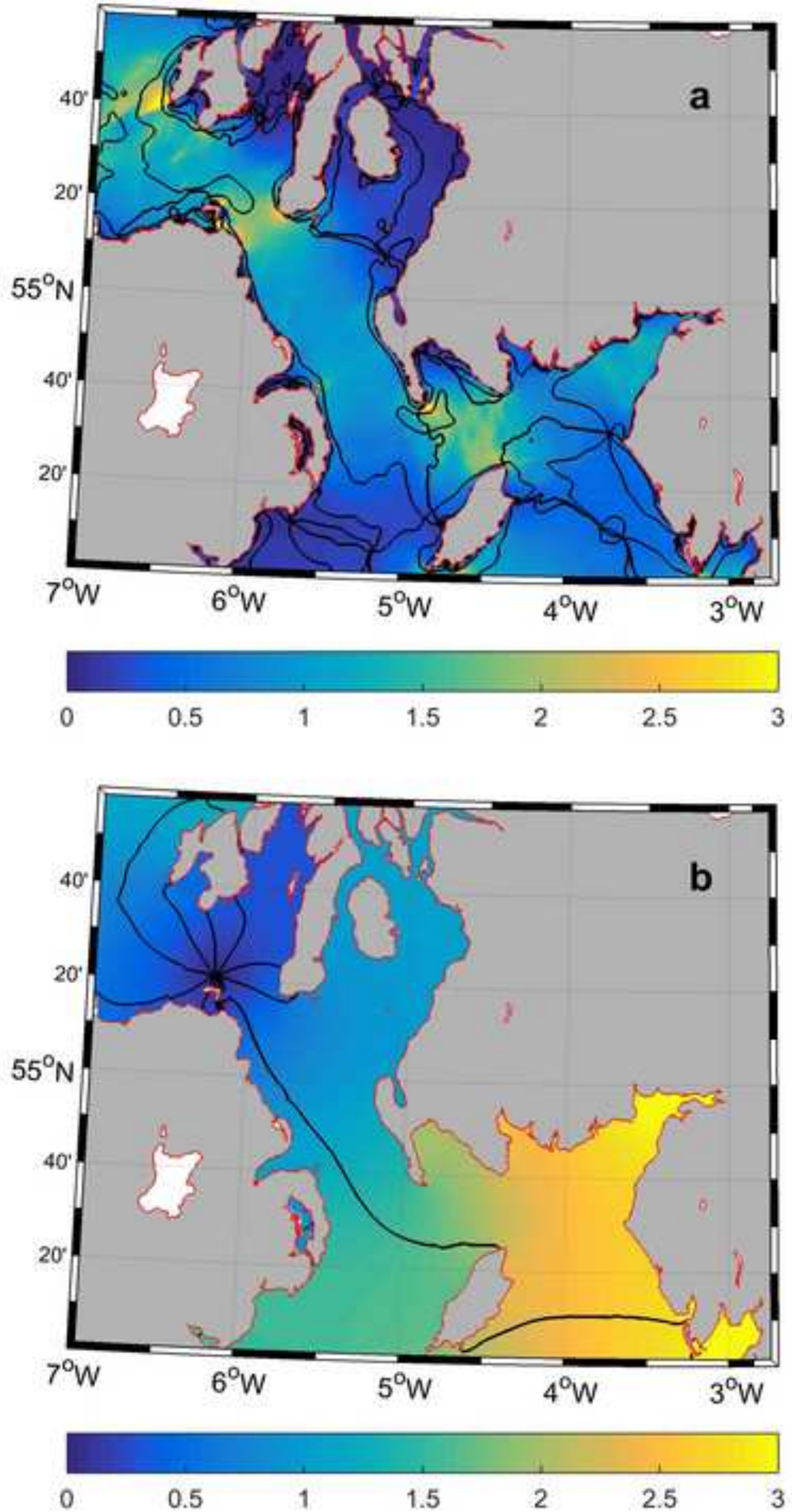
Mean power density (kW/m²)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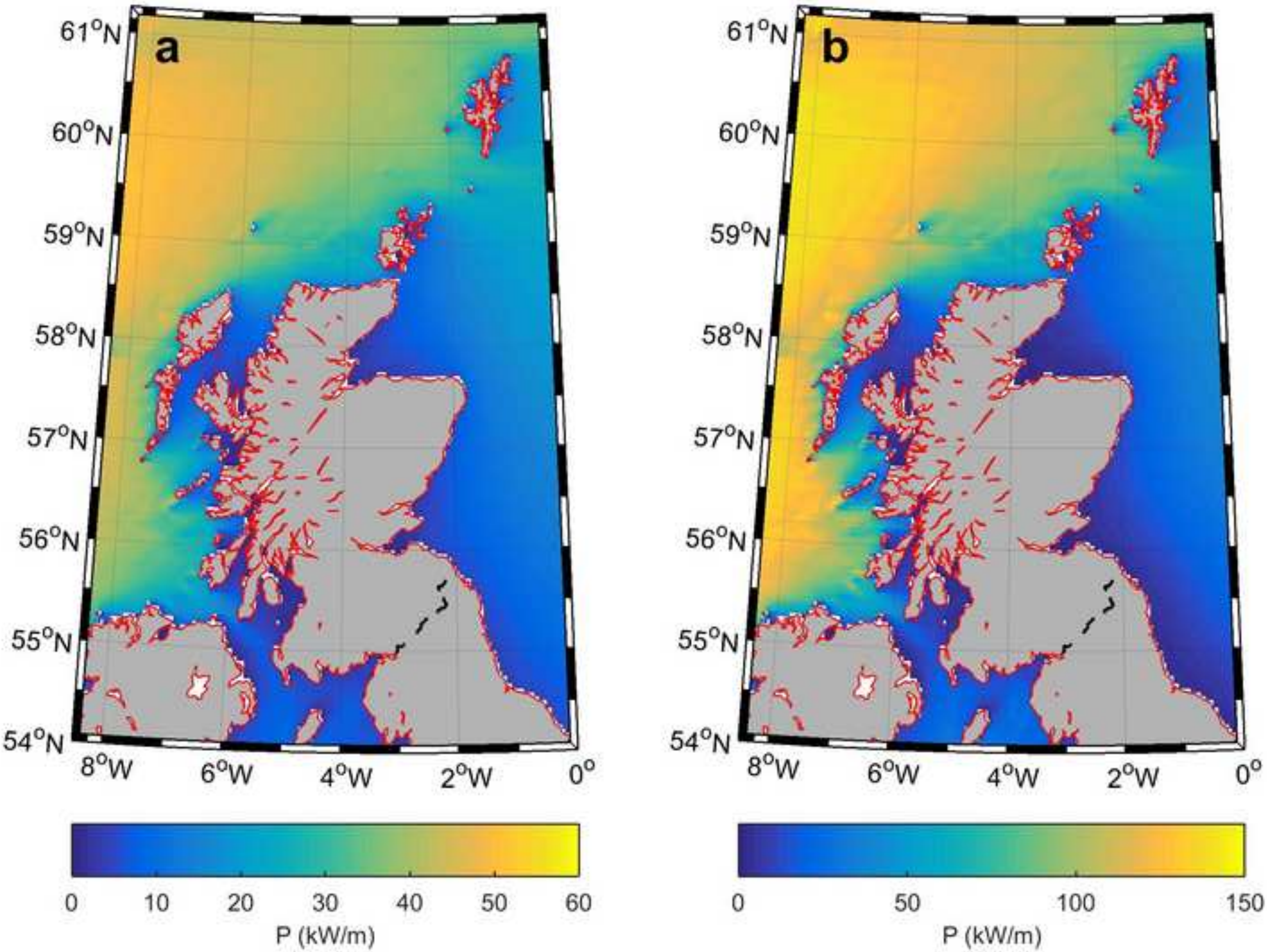
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P (kW/m)
0
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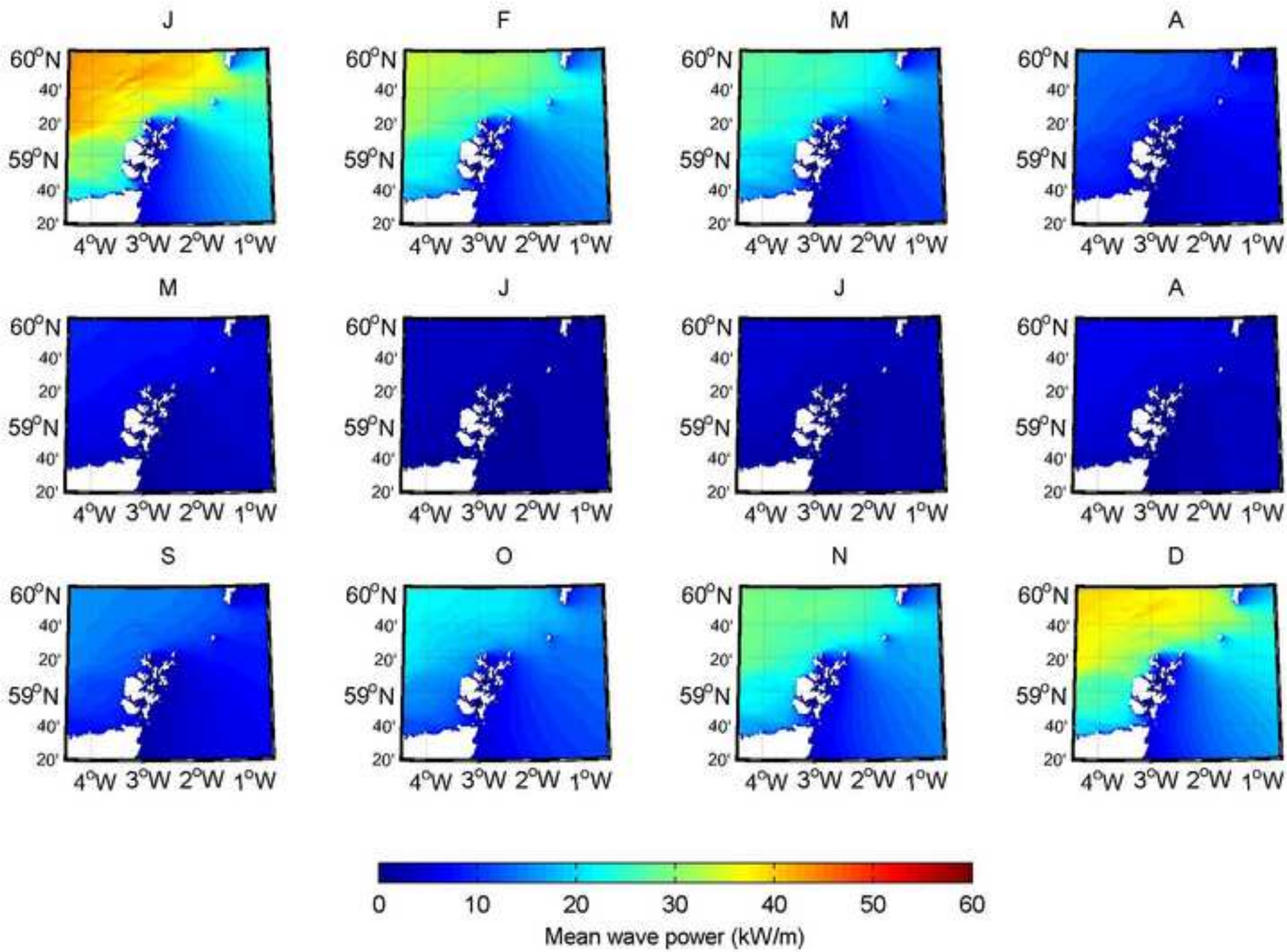
100
150
P (kW/m)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0
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60
Mean wave power (kW/m)

Highlights

- Scotland has been at the forefront of global marine energy developments
- We examine the theoretical and technical wave and tidal resource of Scotland
- We examine past and current commercial developments in Scotland
- In parallel with energetic sites, we suggest that less energetic sites be developed